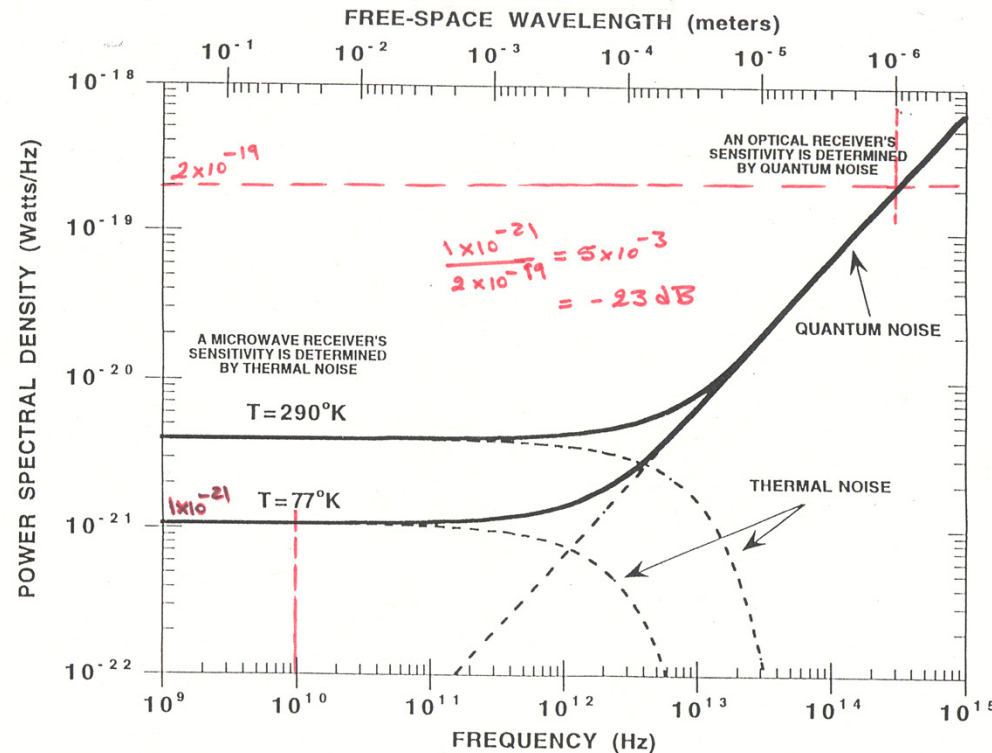# Quantum Limits of Space-to-Ground Optical Communications

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Dominant Limits for Optical and Microwave Frequencies

RF/Microwave frequencies (~10^9 Hz)

- Thermal noise dominates the fundamental sensitivity of a receiver

- Coherent detection gives near optimal performance

- In general, Gaussian noise statistics prevail (central-limit theorem)

Optical frequencies (~10^{14} Hz)

- Quantum measurement noise dominates the fundamental sensitivity of a receiver
- Photon-counting becomes asymptotically optimal at the photon-starved limit
- Heterodyne detection becomes asymptotically optimal at the bandwidth-starved limit
- Noise statistics depend on measurement

Detection Schemes

Coherent detection **scheme:**
- **Superposition of a weak received coherent-state optical signal with a strong local oscillator results in shot-noise-limited performance.**

Direct detection **scheme:**
- **Photon-counting detection of coherent states** (ideal laser light) **can suppress the thermal noise of the detector, receiver and amplifier electronics, such that the output statistics are also shot noise limited.**

Quantum-limited detection **is the result of the residual intrinsic quantum-mechanical uncertainty.**

Photon Information Efficiency (PIE)

Prior to the 1970's
•**It was assumed that the quantum limit on the photon information efficiency [PIE] of an optical comm system was at 1 nat/photon or 1.44 bits/photon, achievable by heterodyne detection.**

Pierce (1978)
•**Recognized that the PIE is unbounded for an optical communication link if an *ideal photon-counting scheme* can be applied.**

Capacity

Shannon's Capacity (classical treatment of information theory)
- Set limits on the highest reliability of data communications, given receiver's architecture.

Holevo's Capacity (quantum-mechanical treatment of information theory)
- Optimized link capacity over the best possible receiver.
  - Theoretical predictions of an optical receiver, optimized via quantum mechanics, to achieve quantum-limited detection
   - *Has not completely materialized yet.*

- New transmission/ detection techniques are required to bridge the gap between the Shannon and the Holevo treatments to achieve the ultimate quantum limits in communications.

Ultimate Quantum Limit

**The ultimate quantum limit for space-to-ground communications**

- **A balance between PIE and DIE (dimensional information efficiency).**

    - **DIE is measured in bits/dimension, where the dimensions are spatial, temporal, and polarization modes.**

    - **Communication links with PIE >> 1 bit/photon are possible, but at the cost of DIE <<1 bit/mode.**

    - **Inversely, DIE >> 1 bit/mode transmission is achievable, but at the cost of PIE << 1 bit/photon.**

Single-Mode Deep-Space Channel Capacity
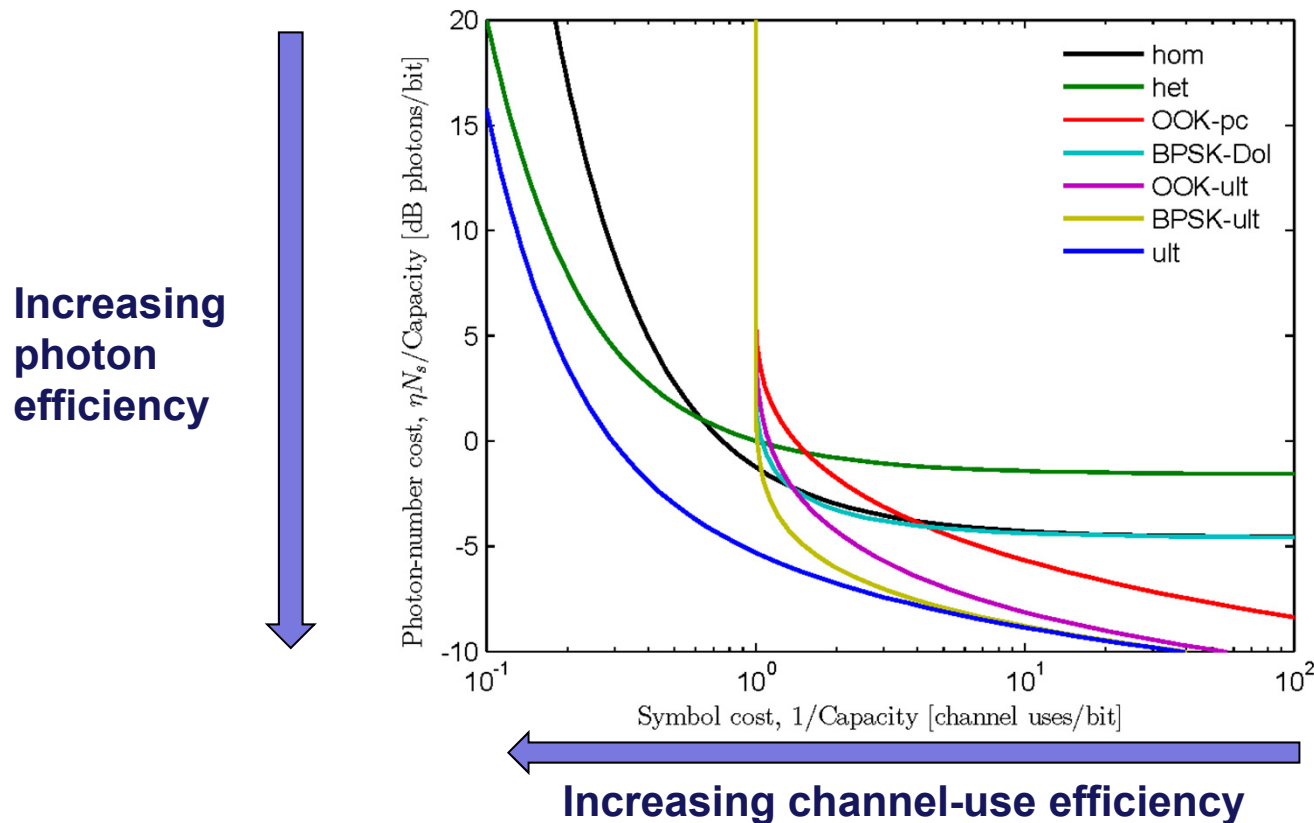
- **Single-mode capacities with several transmitter/receiver technologies, having average photon number constraint**
  - **The 'ultimate receiver' curves are Holevo information bounds**
  - **Specified receiver curves are Shannon information bounds**

Optical Communications at the Quantum Limit

Information bits → Optical Codewords   Optical Codewords → Information-bit Estimates
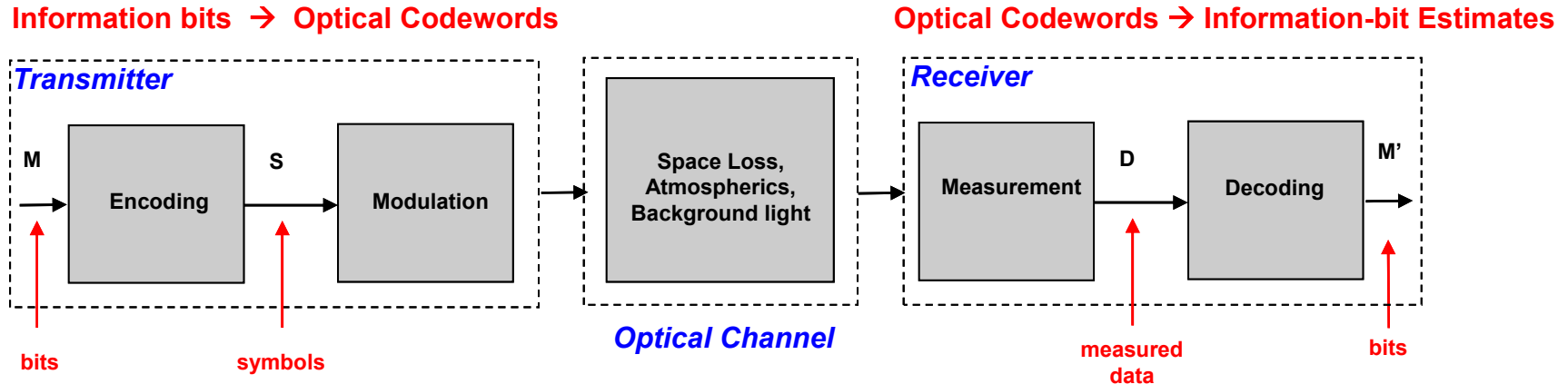
- **Communications link is fundamentally quantum mechanical**
  - **Measurements inherently yield random observations**
  - **Statistics of measurement outcomes determine channel capacity**

- **Quantum limits of free-space optical communications are driven by limits imposed by each of these three components.**
  - **The ultimate capacity of optical communications must therefore optimize over the alphabet of optical states, the priors for the optical states, the measurement at the receiver**

Credit: Baris Erkmen (JPL)

Limits Imposed by the Transmitter

Encoding

- **Optical codes approaching *within a fraction of 1 dB of the Shannon limit* have been developed.**
  - **New concatenated coding has been proposed for quantum optimal coding to *closely approach the Holevo limit*.**

Modulation

- **The best-known approach to achieve the ultimate quantum limit is with coherent state modulation.**
  - **Since exceedingly high (multi-Tb/s) modulation rates are now practically achievable, the modulation bandwidth itself is not a real limitation.**
  - **Phase noise of current lasers is a limitation on the best phase modulation quality for coherent detection.**
  - **Pulse-position-modulation (PPM) in conjunction with photon-counting detection has been shown to deliver quantum-noise-limited performance with unbounded photon efficiency.**
  - **The achievable modulation extinction ratio is limited by the amplified spontaneous emission generated by the source (amplifier).**

Photon Efficiency Limits Due to Finite Extinction Ratio

- **Require 44.5dB extinction ratio to achieve PIE = 10 bits/photon**
  - **The best oscillator modulation extinction ratio achievable today is on the order of 80dB.**
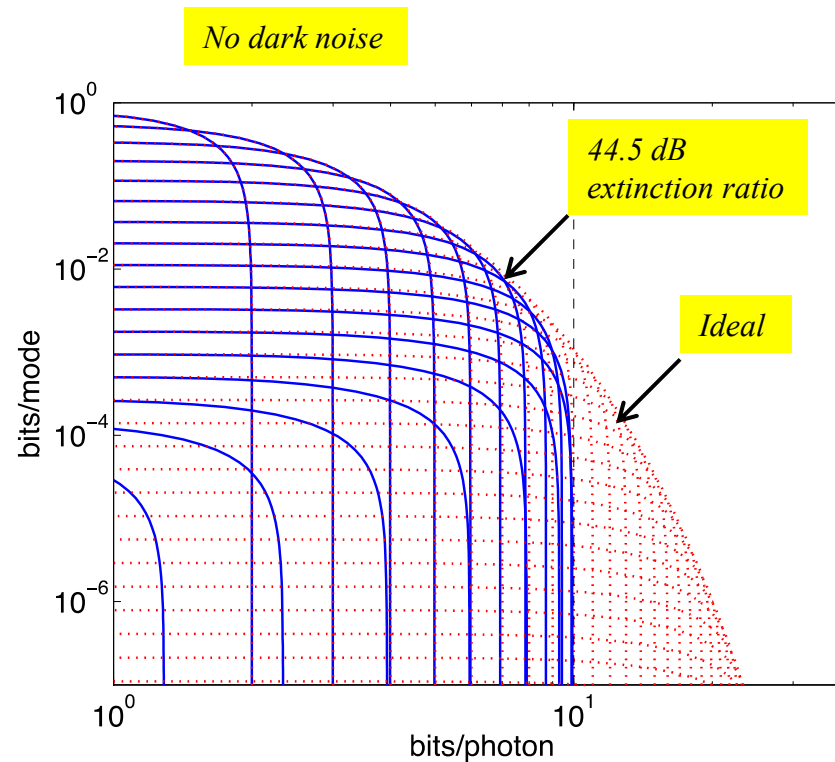
- **Each curve in these plots is the capacity efficiency tradeoff for a given PPM order *M*, and is generated by varying the average number of signal photons.**

Limits Imposed by the Optical Channel

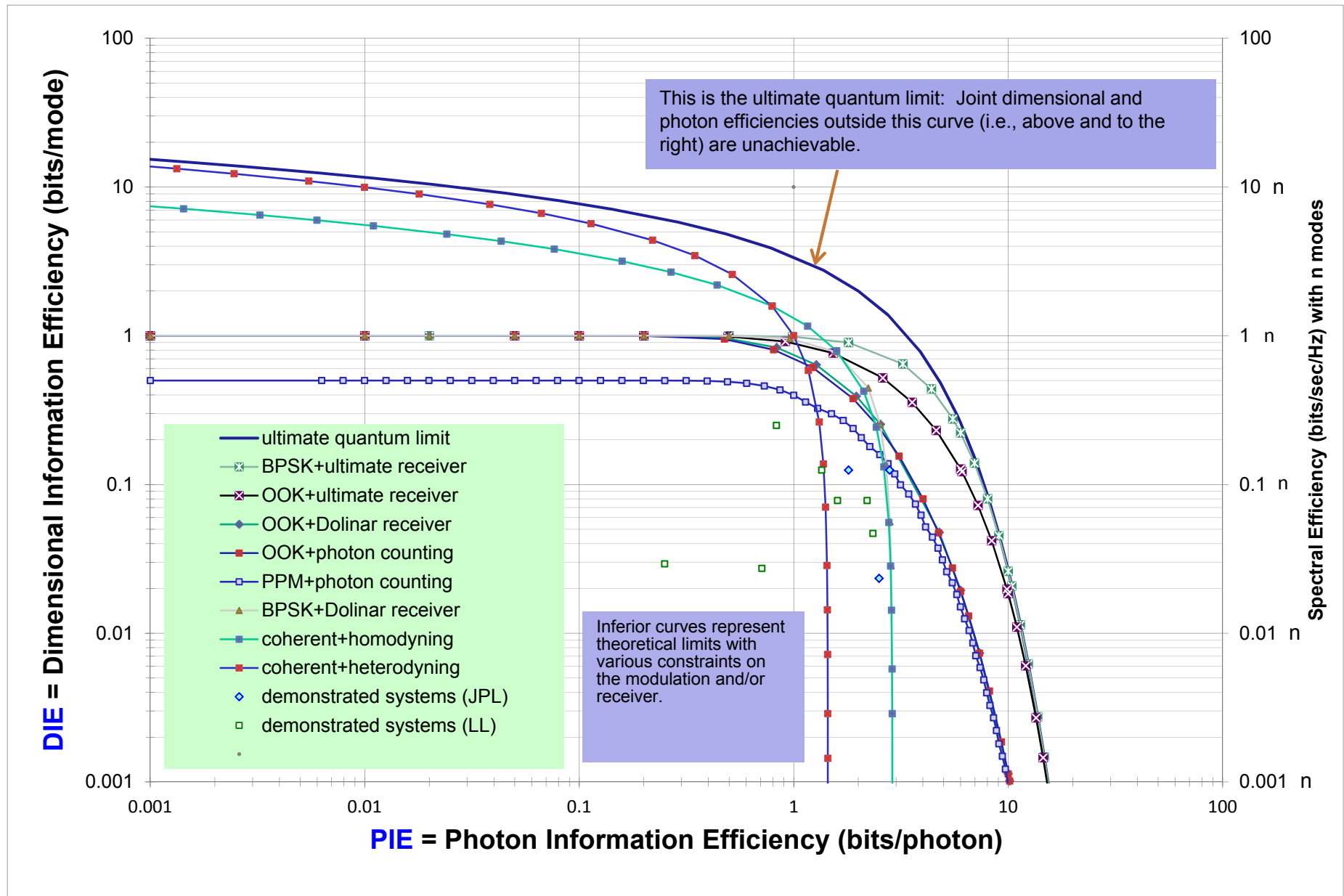The atmosphere causes significant degradation of coherently modulated optical signals.

- Without a daytime-/nighttime-operating adaptive optics (AO) system, significant errors are introduced into the link.

- Background light, inevitably accompanying the transmitted signal onto the receiver, can set severe limitations on achievable link capacity.

- Pulse spreading, a problem with fiberoptics communications, is not a limiter in free-space optical communications since there is very minimal dispersion from the medium.

Limits Imposed by the Receiver
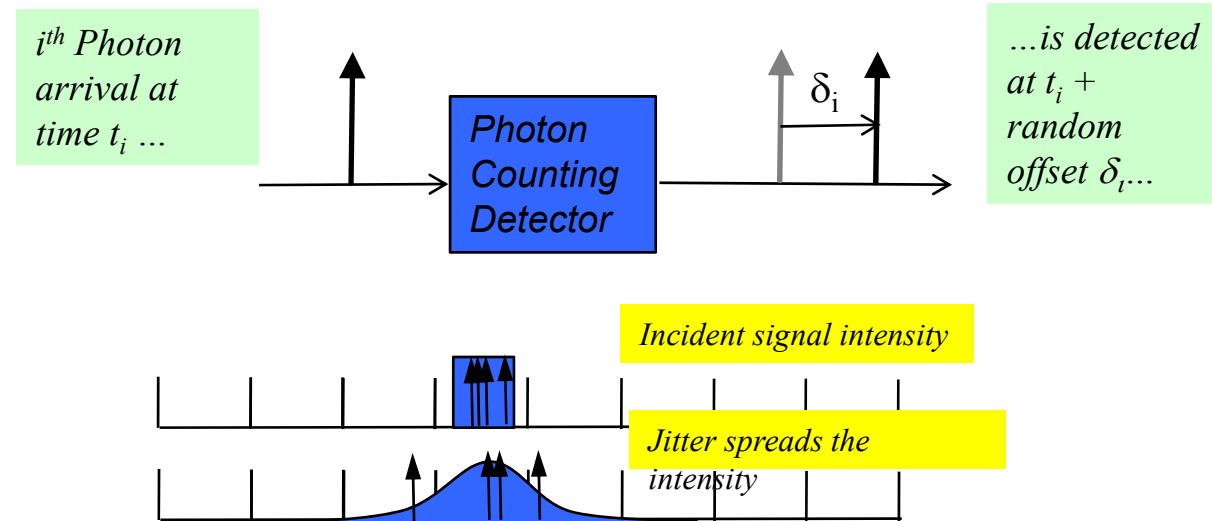
Limitations on the receiver include:

- **Sub-optimal quantum detection**

    - **Photo-detector dark noise**

    - **Photo-detector timing jitter**

    - **Photo-detector blocking loss**

- **Sub-optimal quantum decoding**

- **Quantum limit of noise in optical or electronic amplifiers**

- **Capacity efficiency limits**

Fundamental Free-space Capacity Limits vs. State-of-the-art Optical Systems

Losses due to Detector Jitter

i^{th} Photon arrival at time t_i ...

...is detected at t_i + random offset δ_t...

δ_i

Photon Counting Detector

Incident signal intensity

Jitter spreads the intensity

- Jitter is the ***random delay*** from the time a photon is incident on a photo-detector to the time a photo-electron is detected.
- Jitter losses are a function of the ***normalized jitter standard deviation***:

$$\frac{\sigma}{T_s}$$

Jitter standard deviation

Slot-width

Device	σ / ns
InGaAs(P) PMT	0.9
InGaAs(P) GM-APD	0.3
Si GM-APD	0.24
NbN Super-conducting Nanowire	0.03

Jitter limits:

- **data rate**
- **ability to mitigate dark noise**
- **ability to decrease the slot width without incurring loss.**

Photodetector Blocking

- **Certain photon-counting photodetectors are rendered inoperative (blocked) for some time t (dead time) after each detection event**
  - **10 to 50 ns, Si GM-APD**
  - **1 to 10 ms, InGaAs GM-APD**
  - **3 to 20 ns, NbN Super-conducting Nanowire**

- **Mitigating Blocking**

  - **Decreasing the peak incident photon rate (per detector)**

  - **Temporally**
    - *Increase the slot-width and reduce the photon rate, while preserving the photons/slot.*
    - *Reduces impact of blocking, but lowers the date rate (bits/s), and integrates more noise*

  - **Spatially**
    - *Increase Focal length, to decrease signal intensity in the focal (detector) plane*
    - *Integrates more noise*

Summary

- **For a pure loss channel, the ultimate capacity can be achieved with classical coherent states (i.e., ideal laser light)**
  - **Capacity-achieving receiver (measurement) is yet to be determined.**
  - **Heterodyne detection approaches the ultimate capacity at high mean photon numbers.**
  - **Photon-counting approaches the ultimate capacity at low mean photon numbers.**

- **A number of current technology limits drive the achievable performance of free-space communication links.**

Summary, cont.

- **Approaching fundamental limits in the bandwidth-limited regime**
  - **Heterodyne detection with high-order coherent-state modulation approaches ultimate limits.**
    - SOA improvements to laser phase noise, adaptive optics systems for atmospheric transmission would help
  - **High-order intensity modulation and photon-counting can approach heterodyne detection within approximately a factor of 2.**
    - May have advantages over coherent detection in the presence of turbulence

- **Approaching fundamental limits in the photon-limited regime**
  - **Low-duty cycle binary coherent-state modulation (OOK, PPM) approaches ultimate limits**
    - SOA improvements to laser extinction ratio, receiver dark noise, jitter, and blocking would help
  - **In some link geometries (near field links) number-state transmission could improve over coherent-state transmission**